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Thermal Insulation Performance and Thermal Conductivity Evaluation of Natural Stones by Infrared Thermography

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***Abstract* –** Natural stones are one of the various materials utilized as thermal insulators in building coating. The common usage of natural stones such as marble, travertine and andesite due to their natural and decorative appearance brings the necessity of proper characterization of these stones with respect to thermal performances. There different natural stone types of Turkey with different formation mechanisms were evaluated regarding the thermal conductivity, heat conductance and availability to be used as thermal insulators were evaluated. The infrared thermographic analyses of marble, travertine and andesite samples were conducted and the results were cross-checked with other physical and chemical characterization tests. The thermal performances were compared and the most suitable natural stone type was determined to be utilized as insulators in building coating.

***Keywords*:** Infrared thermography, Natural stones, Thermal insulation, Heat transfer, Thermal conductivity.

1. Introduction

The heat insulation of buildings is a very important subject with respect to energy saving, comfortable living conditions and legal regulations. There are various materials used as thermal insulators and applied as building coating. Natural stones are one of those materials with high preferability due to their decorative view. Three different types of natural stones (marble, travertine and andesite) with different formation mechanisms and origins were investigated regarding their thermal conductivity and heat transfer properties by infrared thermography. The utilization of these stones as decorative and insulating building coating material was evaluated.

Infrared thermography is a non-destructive temperature mapping method used in several industries including engineering where surface temperature is significant. This technology provides substantial information in analyzing and characterization of materials and structures. The radiated thermal energy from the surface in the infrared band is transformed to a visible image with color spectrum representing each energy level by infrared thermography (Meola et al., 2005; Avdelidis et al., 2007). Thermography is commonly considered as a qualitative method which is used primarily to indicate variations in thermal resistance on a wall or roof (Grinzato et al., 1998). Such methods generally consist of the thermal stimulation of the object and monitoring of its surface temperature variation during the transient heating or cooling phase involving heat conduction in solids (Popov et al., 1999).

Heat transfer or conduction can be described as the energy transfer due to temperature difference of adjacent structures. The amount of transferred heat depends on several factors such as porosity, shape, temperature interval, moisture and uniaxial pressure (Clauser and Huenges, 1995; Singh et al., 2007). Thermal insulation is a significant method in energy saving. The systems of thermal insulation can be characterized by thermal conductivity. Thermal conductivity is primarily controlled by the mineral composition and texture of the rock (Popov et al., 1999). The thermal conductivity of a rock is determined by measurements of temperature gradient in the rock and heat source. The empirical formula to calculate the thermal conductivity is Fourier's Law and expressed in Eq.1 where ${}^{\Delta Q}/_{\Delta t}$ is the amount of heat transferred per unit time (W), k is conductivity (W/m.K), A is the cross-sectional surface area (m^2), ΔT is the temperature difference (K) and Δx is the thickness of the rock sample (Altay et al., 2001; Görgülü, 2004).

$$\frac{\Delta Q}{\Delta t} = -k\ A\ \frac{\Delta T}{\Delta x} \qquad (1)$$

There are several worthy studies on the utilization of infrared thermography in material characterization such as Gündüz et al. (2001), Demirdağ and Gündüz (2003), Vosteen and Schellscmidt (2003), Meola et al. (2004), Nilica and Harmuth (2005), Meola (2007) and Shi et al. (2007). In addition, the insulating performance of various rocks or insulating materials were investigated thoroughly by many scientists (Al-Kassir et al., 2005; Synnefa et al., 2006; Barreira and Freitas, 2007; Durmus and Görhan, 2009). The evaluation of thermal conductivity, heat transfer capacity and thermal insulation of samples were conducted depending on physical and chemical characterization and infrared thermography of each sample as stated in literature.

2. Material and Method

Three different rock types such as marble, travertine and andesite, representing the natural stones of Turkey, with different properties and formation mechanisms were selected for thermal imaging (Fig. 1).

Fig. 1. Illustrative samples among 3 samples of marble, travertine and andesite respectively.

The three marble samples, labeled as Muğla White, gathered from Muğla vicinity in western Turkey were characterized with respect to related physical and chemical properties. The travertine samples, labeled as Denizli Travertine, were gathered from the city of Denizli, Western Turkey while the Menemen Andesite samples were gathered from Menemen, Western Turkey and characterized as well. The average physical and chemical properties of all samples categorized as marble, travertine and andesite are listed in Table 1. All samples were dimensioned as 60x60x2 centimeters to accurately compare the thermal performances and the average measurements of 3 different samples from the same region were taken into account as representative data. The differences in porosity and structural matrix were the main parameters in determination of sample types.

Table 1. Related average physical and chemical properties of rock samples

	Marble	***Travertine***	***Andesite***
Dry Unit Weight (kg/m^3)	2.68	2.37	2.40
Avg. Porosity (%)	0.16	4.92	4.17
Avg. Moisture Content by Wt. (%)	0.14	0.22	2.20
Avg. Water Absorption by Wt. (%)	0.07	1.37	5.13
Avg. Thermal Conductivity (W/m.K)	3.88	2.17	1.35
SiO_2 content (%)	0.20	0.26	61.65
CaO content (%)	54.79	55.12	5.28
MgO content (%)	1.02	0.31	0.74
Al_2O_3 content (%)	0.06	0.07	15.18

The experimental setup simply included a thermal camera, a laboratory type-newly designed artificial heat source with digital temperature adjustment and timer, a camera and an infrared thermometer (Fig. 2).

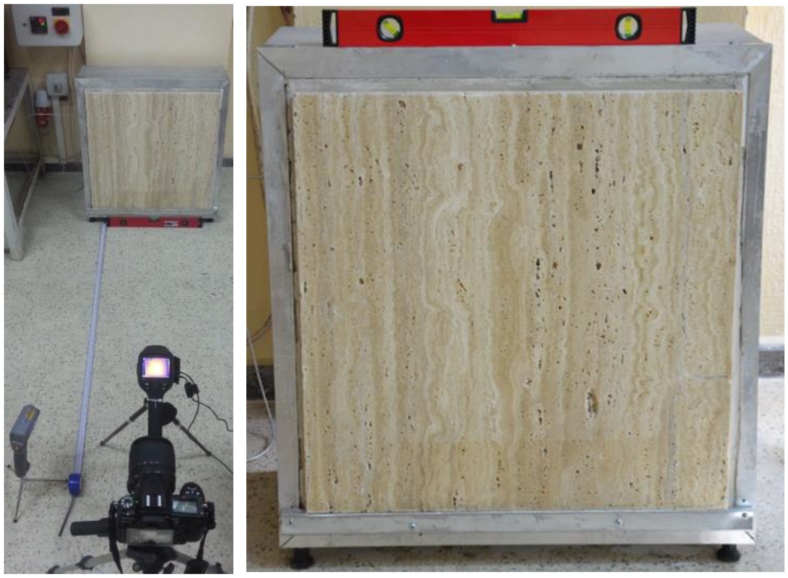

Fig. 2. Equipment used (thermal camera, heat source, timer and temperature adjustment panel, infrared thermometer, camera) and experimental setup.

The experimental setup was arranged regarding the technical specifications of the thermal camera used (Table 2). The field of view and accuracy was taken into account to adjust the setup and a distance of 1.8 meters from the rock surface was fixed while the ambient temperature and humidity was varied between 17-22°C and 50-55% respectively. The artificial heat source, originally designed for homogeneous heat distribution along the surface area was used to transfer heat on the rear side of the samples (Table 2).Temperature level of the heat source surface was adjusted digitally, kept constant and checked simultaneously by an infrared thermometer. Several measurements were taken and recorded by thermal imaging for 3 different surface temperatures (40, 60 and 80°C) during 30 minutes for each sample. Every temperature level was adjusted and setup was prepared individually regardless of previous measurements. The samples and heat source were reposed to reach constant ambient temperature prior to measurements.

Table 2. Technical specifications of thermal camera and heat source (laboratory type)

Thermal Camera	
IR resolution	240 × 180 pixels
Thermal sensitivity	< 0.05°C @ +30°C
Field of view	25° × 19°
Focal length	18 mm
Detector type	Focal plane array, Uncooled microbolometer
Image frequency	60 Hz
Spectral range	7.5–13 μm
Object temperature range	.–20°C to +120°C & 0°C to +650°C
Accuracy	±2°C or ±2% of reading for ambient temperature 10°C to 35°C
Heat Source	
Max. power	5000 W
Dimensions	70x70x30 cm
Adjusted current	5.5 A
Status	Fully insulated excluding the front side

3. Experimental Study

The samples were subjected to uniformly distributed heat along their rear surfaces by the laboratory type heat source. The thermal camera readings were recorded as raw data during 30 minutes and thermal images were stored in exactly 0, 10, 20 and 30 minutes of the whole measurement for each sample and each temperature level. An area of measurement (AR1) and a reference spot (SP1) was predefined on the surface of the samples for each thermal image to determine the exact, maximum, minimum and average temperature readings by the help of thermal imaging software of the camera. This data was also screened through the raw data recorded by the thermal camera and listed separately for 40, 60 and 80°C readings in Table 3, 4 and 5 respectively. The temperature difference between the rear-heated surface and front-imaged surface of each sample was calculated empirically. Another empirical approach was the calculation of heat transferred (W or J/s) through the samples to determine the loss of energy quantitively to allow qualitative comparison (Eq. 1). The thermal images of samples at 3 different temperatures after exactly 30 minutes are given in Fig. 3, 4 and 5. The maximum (red spot), the minimum (blue spot), the reference spot (SP1) and area of measurement (AR1) are stated on thermal images.

Table 3. Average measurement readings and calculated heat transferred of 3 different rock samples with a heat source at ~40°C during 30 minutes

40°C - Readings (°C) / Time (min.)	***Marble***				***Travertine***				***Andesite***			
	0	***10***	***20***	***30***	***0***	***10***	***20***	***30***	***0***	***10***	***20***	***30***
Avg. Surface Temperature of Heated Surface	41.0	41.0	40.0	39.0	40.0	41.0	42.0	40.0	41.0	40.0	39.0	40.0
Max. Surface Temperature (AR1)	20.8	23.5	26.3	27.4	26.3	27.6	29.1	30.2	23.4	22.9	24.1	26.2
Min. Surface Temperature (AR1)	16.6	19.4	20.2	20.8	17.3	19.5	20.9	21.6	20.0	20.7	20.9	21.7
Avg. Surface Temperature (AR1)	18.0	21.6	23.5	24.5	18.5	23.5	25.8	27.1	20.7	22.1	23.1	25.0
Temperature Difference Between Surfaces	23.0	19.4	16.5	14.5	21.5	17.5	16.2	12.9	20.3	17.9	15.9	15.0
Reference Spot (SP1)	18.4	23.1	25.7	27.1	18.4	24.4	27.4	29.2	20.6	22.3	23.6	25.6
Heat Transferred (kW)	1.61	1.36	1.15	1.01	0.84	0.68	0.63	0.50	0.49	0.44	0.39	0.36

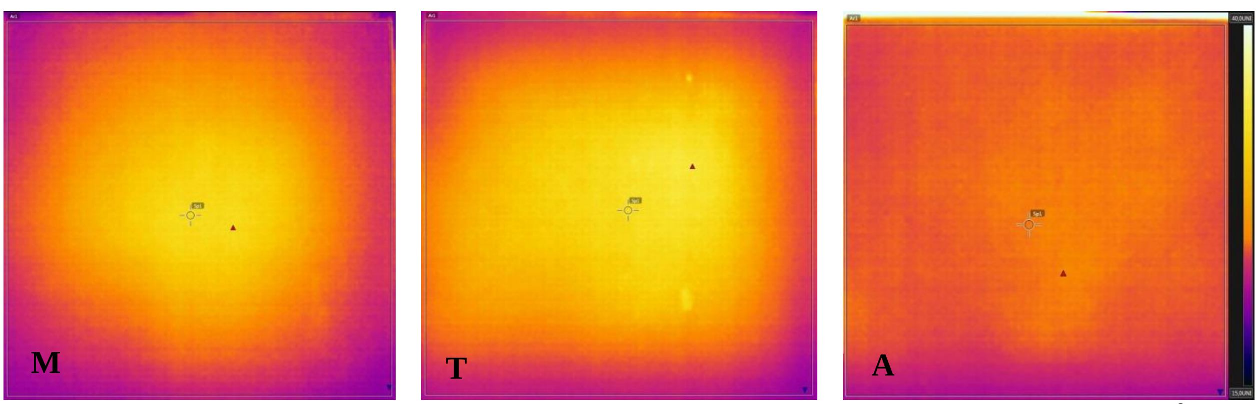

Fig. 3. Thermographic images of 3 different rock samples after 30 minutes with a heat source at ~40°C (constant temperature interval 15 - 40°C).

Table 4. Average measurement readings and calculated heat transferred of 3 different rock samples with a heat source at ~60°C during 30 minutes

60°C - Readings (°C) / Time (min.)	***Marble***				***Travertine***				***Andesite***			
	0	***10***	***20***	***30***	***0***	***10***	***20***	***30***	***0***	***10***	***20***	***30***
Avg. Surface Temperature	60.0	61.0	61.0	60.0	59.0	60.0	62.0	62.0	61.0	60.0	59.0	59.0

of Heated Surface												
Max. Surface Temperature (AR1)	22.1	29.9	33.4	35.5	38.4	60.0	61.4	57.8	24.3	28.9	31.3	33.4
Min. Surface Temperature (AR1)	18.4	21.4	23.4	24.0	18.9	21.6	24.7	26.0	20.5	21.7	22.6	23.0
Avg. Surface Temperature (AR1)	19.5	26.8	29.9	31.6	21.0	30.1	41.0	44.6	22.9	26.2	28.7	30.2
Temperature Difference Between Surfaces	40.5	34.2	31.1	28.4	38.0	29.9	21.0	17.4	38.1	33.8	30.3	28.8
Reference Spot (SP1)	19.5	28.7	32.5	34.5	21.4	32.4	45.1	49.8	23.5	27.3	30.4	32.5
Heat Transferred (kW)	2.83	2.39	2.17	1.98	1.48	1.17	0.82	0.68	0.93	0.82	0.74	0.70

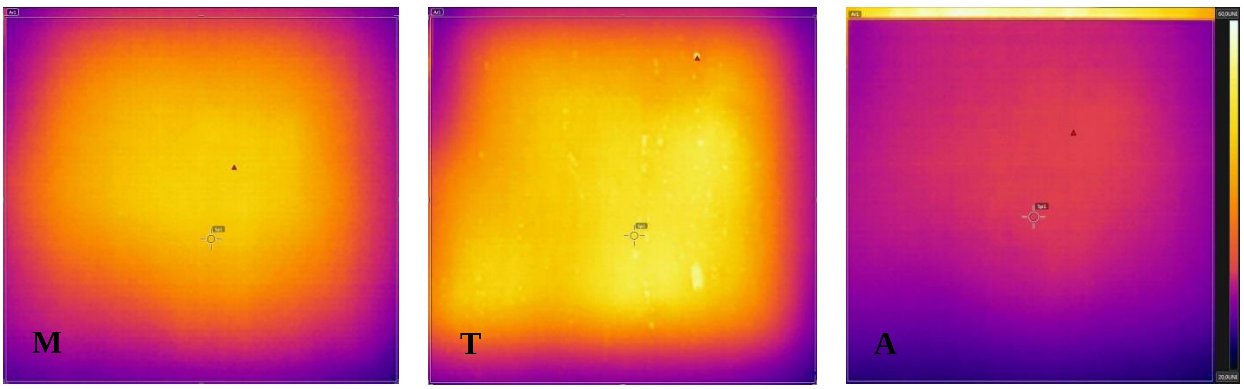

Fig. 4. Thermographic images of 3 different rock samples after 30 minutes with a heat source at ~60^{o}C (constant temperature interval 20 - 60^{o}C).

Table 5. Average measurement readings and calculated heat transferred of 3 different rock samples with a heat source at ~80^{o}C during 30 minutes

80^{o}C - Readings (^{o}C) / Time (min.)	***Marble***				***Travertine***				***Andesite***			
	0	***10***	***20***	***30***	***0***	***10***	***20***	***30***	***0***	***10***	***20***	***30***
Avg. Surface Temperature of Heated Surface	80.0	79.0	80.0	81.0	81.0	82.0	82.0	80.0	80.0	82.0	82.0	82.0
Max. Surface Temperature (AR1)	26.5	36.2	56.2	71.7	45.8	44.6	61.9	79.8	28.7	36.4	40.9	43.3
Min. Surface Temperature (AR1)	19.7	23.5	27.9	28.4	18.6	21.4	25.4	27.3	20.5	24.0	26.1	27.7
Avg. Surface Temperature (AR1)	23.9	32.1	47.3	59.0	21.5	27.7	39.5	49.4	24.8	32.2	36.8	39.3
Temperature Difference Between Surfaces	56.1	46.9	32.7	22.0	59.5	54.3	42.5	30.6	55.2	49.8	45.2	42.7
Reference Spot (SP1)	25.3	35.5	53.7	69.5	21.8	29.6	44.5	56.4	25.0	33.1	38.9	41.7
Heat Transferred (kW)	3.92	3.28	2.28	1.54	2.32	2.12	1.66	1.20	1.34	1.21	1.10	1.04

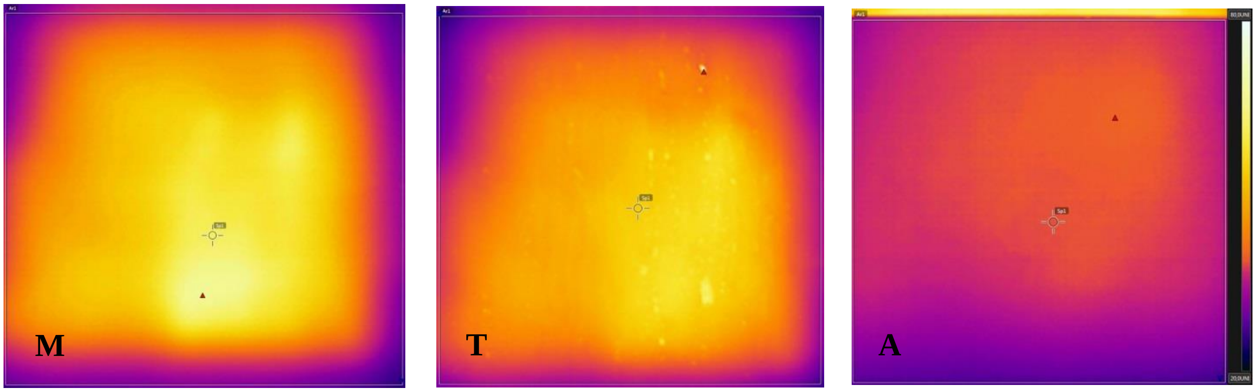

Fig. 5. Thermographic images of 3 different rock samples after 30 minutes with a heat source at ~80°C (constant temperature interval 20 - 80°C).

4. Results and Discussion

The measurement data for 30 minutes was used to create illustrative graphics of the experimental results. The change in the average surface temperature of each sample in time with heat source of 40, 60 and 80°C are shown in Fig. 6, 7 and 8 respectively.

The trend in the surface temperatures of Muğla White and Menemen Andesite were similar during 30 minutes and the surface temperatures at the end of 30 minutes were around 25°C for both when the heated surfaces of the samples were at approximately 40°C (Fig. 6). On the other hand, the surface temperature of Denizli Travertine increased rapidly to 23.5°C in 10 minutes and eventually reached 27.1°C at the end of 30 minutes.

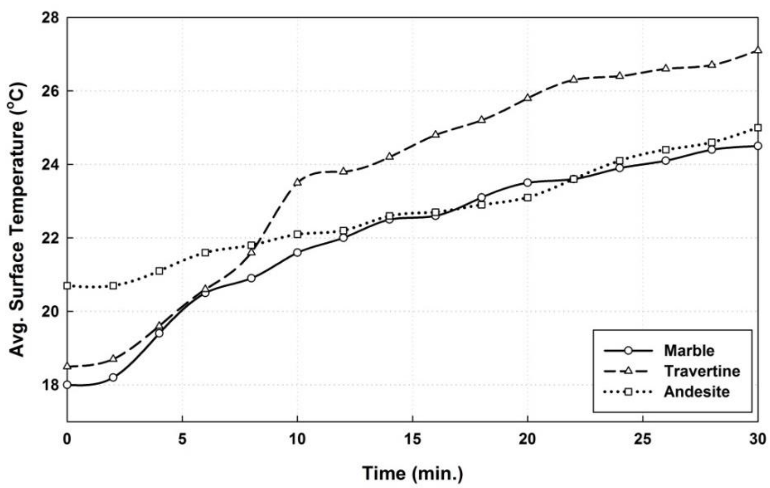

Fig. 6. Change of average surface temperatures of Marble, Travertine and Andesite samples in time with a heat source at ~40°C surface temperature.

The experiments conducted with a heated surface temperature of 60°C revealed similar results as in 40°C. After 30 minutes marble and andesite samples reached a surface temperature of around 31°C. The rapid increase in the surface temperature of travertine in the first 10 minutes was observed again as in 40°C ending with an average temperature of 44.6°C in 30 minutes (Fig. 7). Travertine reached a maximum surface temperature of 57.8°C and approximated the heat source temperature while marble and andesite samples reached maximum of 35.5 and 34°C respectively (Table 4).

The experimental results for a heated surface temperature of 80°C stated that andesite samples still held the heat at the end of 30 minutes and reached an average surface temperature of 39.3°C (Fig. 8). At the same experimental conditions, travertine samples reached a maximum surface temperature of 79.8°C, almost same as the heat source temperature, where marble samples no longer held the heat and reached a maximum surface temperature of 71.7°C with an average of 59.0°C (Table 5).

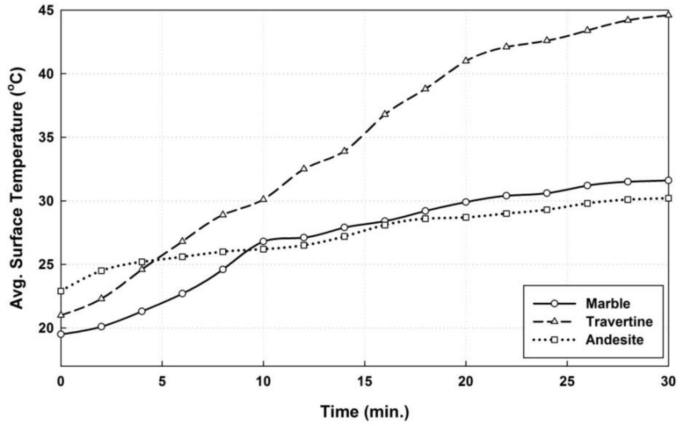

Fig. 7. Change of average surface temperatures of Marble, Travertine and Andesite samples in time with a heat source at ~60°C surface temperature.

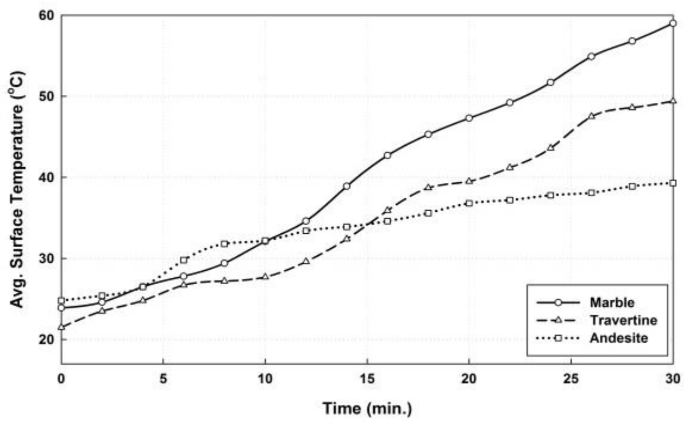

Fig. 8. Change of average surface temperatures of Marble, Travertine and Andesite samples in time with a heat source at ~80°C surface temperature.

It was determined that under same experimental conditions, andesite samples proved the best thermal performance with respect to utilization as insulation material in building coating. Travertine samples were revealed to be poor heat insulators since the most rapid conduction of heat between surfaces occurred in travertine samples. In addition, the maximum surface temperatures reached in different heat source levels were also measured in travertine samples. Marble samples held heat as well as andesite in low heat source levels, however in experiments conducted in 80°C, marble samples had higher average surface temperature readings than travertine samples. The mechanism of heat transfer and thermal insulation should be defined in terms of porosity, thermal conductivity and texture of rock samples. Continuous studies and measurements would be accomplished in the course of this study to accurately characterize different types of natural stones from different regions and origins to determine the factors affecting thermal performances and applicability as insulation materials.

5. Conclusion

Natural stones are most widely used as decorative insulation materials in building coating. The thermal performance of these stones should be determined accurately to avoid energy wasting in building insulations. Three different types of natural stones of western Turkey (marble, travertine and andesite) with different formation mechanisms and origins were investigated regarding their thermal conductivity and heat transfer properties by infrared thermography in this study. The samples were subjected to uniform heating under 3 different temperature levels and the thermal images were taken as well as the recorded data during 30 minutes for each sample.

The highest thermal insulation performance was determined in andesite samples with high porosity and low thermal conductivity values. Andesite samples also held heat during 30 minutes of heating with low heat conductance to the surface due to its porous structure, high silica content and rigid structural matrix. The porous structure should decrease thermal conductivity due to the presence of air in the pores, adding insulation character to the samples. In addition, the temperature distribution should be uniform for a uniform surface heating in case of a homogeneous material. However the travertine samples, with high porosity and medium thermal conductivity, presented the lowest thermal performance. The perforated surface of travertine samples caused a defect in thickness in specific spots that resulted in high surface temperature readings. The holes and cracks on the surface (Figs. 1 & 2) were easily determined in the thermographic images (Figs. 3, 4 & 5) of travertine in all temperatures causing high surface temperature readings. Filling should be applied to travertine prior to installation as building coating. The marble samples performed similar to andesite in low temperatures but couldn't hold heat in high temperatures due to its non-porous crystalline structure and high thermal conductivity.

It is revealed that, infrared thermography can be used efficiently in determination of thermal performances of rock samples if it is applied in correlation with physical and chemical characterization results and empirical calculations.

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